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Research Development and Demonstration Plan

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Executive Summary

There is a high likelihood that in the coming decades global climate change will have tangible effects on California's natural environment and economy. In the event of rapid and/or extreme shifts in the climate system, these effects could be substantial and could entail high economic costs. At the same time, California is already starting to undertake new policy initiatives to abate greenhouse gas emissions, and national and international policies for addressing climate change, while not yet fully formed, are almost certain to emerge and will themselves affect California's economic and natural resource policy process.

Economic methods are the primary tools for evaluating the socioeconomic implications of climate change and the costs and benefits of policy responses. Economics is also the primary disciplinary source of theoretical and computational tools for integrating climate science and policy. Analyzing and formulating policy responses to climate change in California is, broadly, a problem in the economics of risk and uncertainty. Applying state-of-the-art methods in decision analysis and computational modeling will allow California's policy makers to better understand the complex and uncertain nature of potential impacts, how to address the economic risks they entail, and how policy actions can be coordinated across different sectors of the economy and different regulatory areas.

Simultaneously, policies to mitigate carbon and other greenhouse gas emissions may have a major impact on California's energy system. New research on the determinants of energy demand, the nature of energy-saving technological change, and the increasing role of information technology and its relation to energy trends will help California design carbon abatement policies that are consistent with the state's continued growth and economic vitality.

The research areas and priority activities discussed in this roadmap are as follows:

Computational modeling and decision analysis: Develop new models and software for integrated economic and policy-relevant analysis capable of: (1) addressing fundamental uncertainties in climate-related costs and benefits, (2) formulating decision strategies that are robust across a variety of future climate and economic scenarios, and (3) facilitating policy responses to rapid, severe, and unanticipated climate impacts.

Climate change impacts and adaptation: Extend existing research and develop new economic models to better understand key risks, particularly from potential abrupt and extreme changes in the climate, and the costs of mitigating or adapting to them.

Economics of energy efficiency: Apply concepts and methods from the emerging field of behavioral economics to better understand the nature of consumers' energy-efficiency investment decision making and its implications for policy.

Technological change: Conduct theoretical and econometric research to determine how price-induced innovation, learning effects, and government policies have affected trends in energy efficiency in the California economy; develop a California-focused energy technology simulation model that can apply this research to project future trends and analyze policies to promote technology adoption.

Information technology and energy: Determine the past, present, and projected future relations between the diffusion of information technology and trends in energy demand in California.

Revenue recycling: Analyze the economic impacts of different schemes for returning revenues from carbon or energy taxes, or tradable permit revenues, to the state economy.

Air quality and greenhouse gas abatement: Study the benefits of "harmonized options" that simultaneously improve regional air quality and reduce greenhouse gas emissions. Coordinate with CGE modeling work to simulate constraints in criteria pollutant emissions in conjunction with consideration of greenhouse gas emissions.

Regional permit trading: Devise design criteria and implementation plans for intrastate trading regimes for carbon and other greenhouse gases.

Greenhouse abatement cost estimation: Develop improved economic models of the costs of abating non-CO_2 gases.

In the short-term (1–3 years), this roadmap recommends that research address the objectives in the table on the following page.

The PIER Climate Change Research Plan also identifies mid-term (3–10 year) and long-term (10–20 year) goals, all of which build on the short-term work listed above. This roadmap outlines a comprehensive research agenda that would be necessary to fully address the research gaps identified in this document. PIER, however, due to the limited funding, will be able to support only some of the identified areas of research. PIER is currently examining all of the roadmaps to determine which projects should be supported with PIER funding.

Objective	**Projected Cost ($000 per year)**
Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.	$500
Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change. Identify critical "thresholds" of natural and economic systems under such change. Develop models to incorporate existing institutional constraints on key systems. Begin assessment of non-market values of intrastate climate change impacts.	$300
Establish a solid theoretical and empirical body of research on energy-related decision making, using a behavioral economics approach.	$300
Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.	$300
Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.	$150
Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.	$100
Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies, and incorporate these estimates into state-economy-wide integrated assessments of mitigation.	$200
Assess the feasibility of intrastate markets for GHG trading and related mechanisms.	$150
Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.	$150
Total Short-term Cost per Year	**2,100**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected per-year expenditure over the short-term period.

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

Section 1 states the issue to be addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and how PIER plans to address those needs. *Section 3: Background* establishes the context of PIER's climate change work in this area. Section 3.1 discusses existing methods for integrated economic modeling and analysis in the areas of energy and climate modeling, their limitations, and key issues in developing improved integrated modeling tools for application to California's decision making on climate change and energy and GHG-abatement policy. Section 3.2, on the economics of impacts and adaptation, briefly describes current California-focused work in this area and research priorities for extending and enhancing this work. Section 3.3 focuses on key topics relating to energy demand that bear on the central issue of how California can implement the most economically efficient policies for GHG abatement. Section 3.4 deals with two primary issues in integrated policy implementation and the goal of "synergy" between GHG abatement and other policy goals. *Section 4: Current Research and Research Needs* surveys current projects addressing the economic aspects of climate change mitigation and adaptation in California and identifies specific research needs that are not already being addressed by those projects. *Section 5: Goals* outlines proposed PIEREA activities that will meet those needs. *Section 6: Leveraging R&D Investments* identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. *Section 7: Areas Not Addressed by this Roadmap* identifies areas related to climate change research in this area that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being done to address the economic aspects of climate change mitigation and adaptation in California.

Acronyms

CGE	computable general equilibrium
CV	contingent valuation
DOF	California Department of Finance
E/GDP ratio	Energy-to-Gross Domestic Product ratio
EPRI	Electric Power Research Institute
ETC	endogenous technological change
ETSAP	Energy Technology and Systems Analysis Programme
EVRI	Environmental Valuation Reference Inventory
GDP	Gross Domestic Product
GHG	greenhouse gas
GSP	gross state product
HFC	hydrofluorocarbons
IIASA	International Institute for Applied Systems Analysis
IT	information technology
LBNL	Lawrence Berkeley National Laboratory
LRD	Longitudinal Research Database
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
NAST	National Assessment Synthesis Team
NERC	North American Electric Reliability Council
NSF	National Science Foundation
OECD	Organization for Economic Cooperation and Development
PFC	perfluorocarbon
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
RFF	Resources for the Future
STAPPA/ ALAPCO	State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials
TAF	Transport and Analysis Framework
VOCs	volatile organic compounds
WSCC	Western Systems Coordinating Council

1. Issue Statement

Climate change poses a variety of risks to California's natural and economic systems. Formulating and implementing policy responses to address the impacts of climate change in California requires a carefully designed program of basic and applied economic research to assess the nature of these risks from a socioeconomic perspective, their potential costs, and the most efficient policies for either mitigating or adapting to them. At the same time, greenhouse gas (GHG) mitigation will play an increasingly important role in the state's environmental policy making in the coming decades. New economic research is required to better understand the costs and benefits of a variety of both existing and potential policies to reduce California's emissions of greenhouse gases, and to ensure that such policies are consistent with the state's continuing economic vitality.

2. Public Interest Vision

An extensive body of existing research has studied the economic aspects of climate change mitigation and adaptation, and their implications for policy at the national and international levels. To develop economically sound policies for addressing climate change and mitigation in California, new basic and applied research is required. First, improvements in computational modeling and decision analysis are necessary to develop modeling tools that can take account of risk and uncertainty in analyzing climate impacts, response strategies, and GHG-mitigation efforts. Second, researchers need to conduct impact and adaptation studies that incorporate uncertainty and institutional constraints, for various sectors. Third, researchers need to investigate behavioral economics and energy-efficiency investment, to better understand the economic ramifications of energy-efficiency decisions and their application in public policy. Fourth, research needs to explore the role of technological change in the economics of energy production and use. Fifth, researchers should gain a better understanding of how information technology is affecting energy demand in the State, to better inform long-range energy planning. Sixth, researchers should study "revenue recycling," and its potential role in energy or carbon taxes in the State. Seventh, a coordinated research effort needs to analyze the ancillary benefits of GHG mitigation, to integrate air quality and multi-gas GHG-abatement strategies for the greatest benefit. Eighth, economic research must evaluate the concept of regional trading markets for GHG emissions, to assess those markets already in place and to visualize the development of new markets. And ninth, there is a need to improve modeling of non-CO_2 gas abatement, to improve its application in California.

This economic research and development could benefit Californians in a variety of ways: through improved air quality, the more widespread use of energy-efficient technologies, the development and/or use of regional trading markets, better quantification of the costs and benefits of GHG-mitigation options, and more. The successful completion of the work outlined in this roadmap will help all State agencies better evaluate the economics of climate change planning options.

3. Background

It is now well-established that anthropogenic emissions of GHGs are changing the global climate, and that further shifts in the climate system will occur during the twenty-first century. Although subject to considerable uncertainty, there is a high likelihood that these global changes will entail changes to California's climate resulting in both public and private costs for dealing with the accompanying impacts. At the same time, the current national policy and political impasse notwithstanding, it is plausible and perhaps likely that the United States will undertake major efforts to mitigate carbon emissions during the coming decade, possibly within a revised international framework developed from elements of the Kyoto protocol. Such an initiative could have substantial effects on the

American economy at the national, regional, and state levels. Even before the establishment of such broader policy initiatives, California has taken a significant step in enacting a requirement that carbon emissions from motor vehicles sold within the state be reduced by the end of the current decade. Overall, with respect to both GHG mitigation and adaptation to impacts, climate change is very likely to be a key—if not dominant—element of California's environmental management efforts in the coming decades.

More than a decade of increasingly active research, across a range of disciplines, has been devoted to determining the costs of large-scale GHG abatement (particularly CO_2), as well as to estimating the multi-sector impacts and attendant costs of climate change. There are now extensive—in some cases voluminous—literatures on many key aspects of the climate change issue, on both the mitigation and the adaptation sides. Moreover, work is currently under way to assess potential climate change impacts on California specifically (Wilkinson et al. 2002; EPRI 2002). Results from these initial studies indicate specific risks to certain of the state's natural and economic systems, as well as measures that could serve to anticipate and offset damages induced by climate change. These preliminary studies, as well as the large body of existing work on climate change mitigation and adaptation, indicate the need for a broader array of research aimed at understanding the potential costs and benefits of, and appropriate policy responses to, climate change in California.

This roadmap recommends and provides a rationale for research in the areas of economics and policy analysis, building upon and extending previous efforts. The overall aim of this research is to develop and apply theoretical and practical economic methods and tools for addressing the joint problems of: (1) anticipating and responding to the physical and economic impacts of climate change, and (2) designing and implementing economically sound policies for GHG mitigation in California. It is important to emphasize that the roadmap does not provide an exhaustive list of research needs related to climate change mitigation and adaptation in California. There are currently a great number of important questions to be addressed, involving different economic sectors, natural systems, and possible policy responses. This roadmap deals only with a subset of these issues, which are fundamental topics that have been judged to be of key importance and that are likely to yield particularly high benefits from PIER support.

This roadmap reflects two primary themes. First is the need to view the economics of climate change, and policy planning in response to climatic impacts, in terms of risk and uncertainty. Despite rapid scientific advances, the exact nature of the impacts of climate change on California cannot be predicted with certainty, and further research—while narrowing the uncertainty—cannot be expected to eliminate it. Thus, anticipating the possible character of climate change impacts and making the necessary investments to address them is analogous—albeit on a much broader scale—to the everyday problem of buying insurance against more prosaic risks. This point-of-view is strongly reinforced by the emerging scientific understanding of "abrupt" or "nonlinear" climate change (described in Section 3.1 below), which might entail impacts on California that are both more significant and more sudden than has been heretofore anticipated.

The second theme is the need for new and innovative research to fundamentally improve our understanding of the determinants of energy demand and the role of energy in the aggregate state economy. Such research is essential in order to improve upon existing, very imprecise estimates of the costs of GHG abatement (particularly as it relates to carbon) on a large scale. This problem also involves uncertainty, but from a somewhat different direction. That uncertainty is the hallmark of the climate problem with respect to climate *science* is widely known and figures prominently in policy and political debates. It is also a central guide to the scientific research community's ongoing efforts to improve knowledge of the climate system, potential changes therein that may be under way, and the possible impacts on biological, ecological, and other natural systems. The *economic* dimension of uncertainty related to climate change, by contrast, is much greater than is commonly understood. This uncertainty arises directly from long-standing gaps in research on the microeconomics of consumers' and firms' energy-related decision making and on the nature of energy-saving technological change.

It is important to highlight one other aspect of this roadmap. Although research on all the topics discussed would have a clear, practical benefit for California's climate change analysis, planning, and policy making, a number of points emphasize research that may appear to be more "basic" than "applied." The reason is that, in a number of critical areas, methodological advances over existing approaches (both theoretical and empirical) are required to better serve the needs of policy makers.

3.1 Computational and Decision-Analysis Tools for Integrated Risk Assessment

The central goal of PIER research and allied efforts is to develop tools that will enable state policy makers to carry out integrated analysis of potential climate impacts, response strategies, and GHG-mitigation efforts in a risk-assessment context. The need for integrated analysis of environmental, economic, and policy issues became a central theme in climate policy in the mid 1990s, and has been recently reaffirmed in the National Assessment (NAST 2001a,b).

This type of analysis at the state level would be an adaptation of what has come to be known as "integrated assessment" of global climate change when undertaken in the context of the national or global economy: fully linked quantitative analysis of the interactions among underlying economic factors, energy supply and demand, and GHG emissions and climate-related damages. In its most ambitious form, integrated assessment is global cost-benefit analysis, in which the marginal costs of GHG abatement are dynamically equated to the marginal damages from climate change over timescales of up to a century (Nordhaus 1994).

In the context of the state economy, this approach to integrated assessment is inappropriate: the costs and benefits of California GHG abatement efforts cannot be meaningfully weighed in this manner. Even short of full cost-benefit analysis, integrated economic analysis of climate change mitigation and adaptation at the state level will differ in fundamental respects from national-level analysis in three ways. First, there is a high likelihood that state-level policies to mitigate GHGs and those to address adaptation to climate change impacts will be pursued somewhat independently. Second, state-level mitigation efforts are likely to arise both locally and in response (in the long run) to national policy mandates. Third, despite the size of California's economy, it cannot be modeled independently of either the national economy or of state-specific international trade flows.

Despite such differences, however, it is meaningful to consider forms of "integrated assessment" at the state level. The aim of such analysis would be to assess, at the level of the statewide economy, the costs and potential benefits of both climate change impacts and efforts to mitigate GHG emissions. This type of approach is essential to account for these aggregate impacts, as well as to study the complex interrelationships among sectors in adapting to climatic impacts and absorbing the costs of mitigation. The following discussion focuses on the key issues involved in the identification and development of a theoretical and computational platform that will support an appropriate integrated California analysis.

3.1.1 Key Limitations of Current Modeling Approaches

Economic analysis of climate change mitigation and adaptation has come to be carried out primarily through the construction and application of large-scale numerical simulation models (Weyant 2000). The dominant modeling approach for this purpose has been the so-called "computable general equilibrium (CGE)" paradigm. The key elements of this approach include: (1) market equilibrium of supply and demand for goods and services (including, but not limited to, energy), (2) rational behavior on the part of consumers and firms (i.e., utility maximization and cost minimization, respectively), (3) a representation of the (national or global) economy over long time horizons, and (4) perfect foresight on the part of consumers, firms, or a representative decision maker with respect to all future events and the consequences of all actions. In practice, CGE models used for integrated assessment (or for other applications) do not generally take explicit account of uncertainty; they are deterministic in that they assume perfect knowledge of the present and future values of all included variables and parameters.[1]

The use of such models for economic and policy analysis of energy issues began in the 1970s and has steadily expanded in scope and complexity. More recently, many of these originally energy-economic models have evolved to include environmental factors, with the goal of integrated assessment as described above. In fact, that capsule description understates the emerging role of the economics-based integrated assessment (IA) models. In practice, the economic concepts and methods embodied in these models have emerged as a dominant pathway through which *scientific* information on climate change is

[1] Theoretically, the general equilibrium paradigm—originated primarily by Arrow and Debreu in the 1950s—can be extended to incorporate uncertainty. Implementing this extension in practice, however, confronts substantial hurdles, some of which are noted in the succeeding discussion.

organized and transmitted to policy makers. In this respect, economics-based models play a role beyond simply estimating costs and benefits of climate-related policies and impacts.

The standard CGE approach, while usually applied to national or international economies, can (with appropriate modifications) also be applied to a state economy such as California's. Indeed, CGE modeling is currently applied to taxation and revenue analysis in California (Berck et al. 1996; see also Section 4.6, below). An extension of this existing modeling capability to energy and climate issues can provide an initial benchmark for estimating approximate, aggregate economic impacts of climate change and GHG mitigation policies. At the same time, however, it is essential to begin the study of potential integrated modeling tools for California that extend and possibly transcend the deterministic CGE approach. Key reasons for such an effort are summarized in the following discussion—very broadly, they have to do with the need to rigorously address different types of uncertainty.[2]

The creation of a single integrated economic modeling tool for California must take account of basic issues in IA modeling that are reflected by the wide range of results from existing models. As Kann and Weyant (2000) point out, this variation "has made it difficult for scientists and policy makers to know how to use the results of integrated assessment models. Thus, policy makers' high demand for reliable model results has not been fulfilled." The variation can be ascribed to different assumptions about economic and physical processes both exogenous and endogenous to a given model, different value judgements that bear on model structure and output, and different modeling simplifications that are made for computational reasons.

In the context of climate change analysis, a fundamental problem that cuts across these categories is how future events—both economic and environmental—are represented. As noted above, with few exceptions, CGE- type IA models are deterministic and are focused on determining optimal or least-cost policies over very long time horizons under conditions of certainty. Typically, a small number of "most likely" scenarios are the basis for analysis. Baseline paths for economic growth, energy demand, and other key variables are selected, often on a century-long timescale. Optimal or equilibrium solutions with these paths are then calculated, and in policy applications, the costs of hypothetical carbon taxes or similar future measures are derived.

It is sometimes emphasized that baseline paths and policy-induced alternatives are not "predictions" or "forecasts" of what will happen, but simply estimates of a plausible set of future events and their implications. In practice, however, it is clear that in diffusion from the academic to the policy arena, this type of calculation does become a de facto prediction, and is treated as such in both policy and political debate. Indeed, the most straightforward interpretation of deterministic model calculations is that they are, in fact, predictions or forecasts. As such, the weight commonly placed upon them is puzzling and, from a policy perspective, troubling. It is a truism that the track record of economic

[2] This discussion draws in part upon Kann and Weyant (2000).

forecasting in general is poor. With respect to long-run energy-economic modeling in particular, it is well known that conventional wisdom has frequently been proven wrong. Even short of the fact that forecast error is unavoidable and inevitable, standard models incorporate a wide range of more-or-less equally credible assumptions regarding parameterizations, inputs, and related features (Repetto and Austin 1997; Weyant 2000); the differences among which propagate in time as the models are applied to scenario analysis. The result is a correspondingly wide range of cost and benefit estimates for GHG abatement policies, with no rigorous means of comparison or weighting among them. Several decades of model development and supporting economic research on, for example, values of underlying parameters, have not resulted in convergence to a common knowledge base that would in turn yield convergence of model predictions and estimates. For example, in a recent structured model comparison exercise analyzing the economic impacts of the Kyoto protocol, estimates of U. S. GDP losses from compliance varied by an order of magnitude (Sanstad et al. 2001).

3.1.2 Incorporating Uncertainty

The problems described above are well known and, up to a point, uncontroversial. They all point to the need to incorporate a range of uncertainty types into an eventual integrated assessment model for California. Determining the appropriate theoretical and empirical approach for doing so is itself a major research undertaking. There are a number of examples of uncertainty analysis being undertaken with well-known models (e.g., Manne and Richels 1992; Nordhaus 1994). The computational demands of rigorous uncertainty analysis in an optimization or equilibrium framework, however, are such that drastic simplifying assumptions are generally required to maintain tractability (Kann and Weyant 2000). On an even more basic level, optimization-based uncertainty analysis does not address what has been called "Knightian" or "deep" uncertainty: situations in which values of fundamental quantities are not merely unknown but also cannot plausibly be assigned probability distributions. This description characterizes a broad range of problems in the science and economics of climate change.

The first (and paramount) example is the manifold scientific uncertainty surrounding the evolution of the regional climate. As described in the PIER roadmap on Regional Climate Modeling, projecting the future path California's climate is—and will remain—a problem of considerable technical difficulty. Because exact predictions are beyond our current scientific capability, it will continue to be necessary to evaluate many plausible scenarios for this path in order to conduct economic risk assessment and planning. This analytical requirement strongly indicates the need for a departure from standard deterministic and predictive modeling approaches.

This conclusion is reinforced in the context of potential departures from the standard assumption of gradual and "smooth" climate change. Virtually all research to date on the economics of climate change impacts has been based on this assumption—that is, steady increases in mean global temperature on decadal or century timescales. Within the atmospheric sciences community, however, attention is increasingly focused on the possibility of anthropogenically induced “abrupt” and/or “nonlinear” climate change: dramatic shifts in the climate system on much shorter timescales, of possibly much greater severity (NRC 2002). On a global scale, examples of such phenomena include sudden sea level rise, “runaway” methane releases from the Arctic tundra or offshore clathrates, and disruptions in oceanic thermohaline circulations. In California, such abrupt and/or extreme events (and their consequences) might include prolonged drought, extensive fires, persistent El Niños (with resulting flooding and coastal damage), or the collapse of Sacramento River delta levees.

There is a body of opinion among economists that the key socioeconomic risks from climate change may arise precisely from this type of sudden shift, both on global and regional scales. The economic analysis of both impacts and adaptation under an abrupt/nonlinear scenario in principle differs both in degree and in kind from that appropriate for “smooth” climate change, involving difficult-to-quantity risks, and the need for a computationally intensive consideration of large numbers of scenarios with varying stochastic characteristics.

A second key example is *technological* uncertainty, particularly regarding the future evolution of the energy system and of energy-efficient and/or GHG-reducing technology. A consistent pair of conventional economic and IA modeling findings is that cost estimates for reducing energy use and GHG emissions depend substantially on assumptions regarding the rate and character of technological progress, but that this progress is extremely difficult to predict. Modeling that enables the exploration of a wide range of technology paths that are plausible—but cannot be predicted with certainty—would enable policy makers to better understand the future technological possibilities for GHG abatement and their economic implications.

A third example is the integrated assessment of non-market impacts of climate change. These impacts have been incorporated only to a limited extent in integrated assessment analysis, and further research on them is recognized as a priority within the modeling community. However, the quantification of non-market impacts—for example, valuation of ecosystem services—is controversial. Placing non-market phenomena on an equal footing with conventional goods and services is likely to exceed the frontiers of research for the foreseeable future. Thus, conventional economic and IA models’ treatment of these aspects of climate change—particularly in the context of adaptation—should be regarded as subject to bias and likely to remain so. The reason is that these models require that all goods and services be priced in order to be considered, when determining equilibria. With conventional goods and services, observed market prices serve as the basis for calculation. With non-market goods and services, the absence of such prices poses a substantial hurdle; although there are methods for obtaining proxies, they are controversial, particularly when applied over the long timescales involved in climate impacts. These considerations indicate the desirability of modeling approaches that do not rest solely on price and equilibrium calculations. Preservation of natural systems, or biodiversity, for example, can be much more easily analyzed when these factors can be included directly in simulations, without their value being subject to an optimization calculation.[3]

These considerations point to several conclusions. First, it is important to emphasize that, despite the types of problems just described, large-scale numerical simulation models are essential to provide applied frameworks for decision making and to integrate complex information both within economics and across other disciplines—the requirement of some form of "integrated assessment." In particular, models of this type will be essential for California's economic and policy analysis of climate change. As noted above, application of existing CGE capabilities in the near term can provide initial benchmarks to guide policy and further research. Looking ahead, however, an appropriate research emphasis should be the examination of potential modeling frameworks that address these problems, and that extend or provide specific alternatives to standard deterministic CGE modeling, or both. Following are some key considerations that such an examination should address.

The general goal of integrated assessment modeling for California should be the identification of "robust decision strategies," which are strategies that have a high (but not necessarily certain) likelihood of performing well under a range of possible futures (Lempert and Schlesinger 2000). As noted above, the "range" in question can be environmental (e.g., paths of future climate trajectories) or economic (e.g., paths of technological development) or both. Within certain limits on the scope of the modeling exercise, such strategies can be determined within an optimization and equilibrium framework that incorporates uncertainty. The scope is defined in particular by the number of economic sectors represented, the time horizon over which the analysis is conducted, and the availability (or lack) of probability distributions for modeled variables and parameters. Thus, the initial question to be addressed is the appropriate size and scope of California's ultimate integrated assessment modeling framework for climate and GHG mitigation policy analysis. It is important that the framework chosen allow for dynamic policy making with learning—that is, that decisions can be modeled dynamically over time in a manner that incorporates the emergence of new information regarding climatic impacts, technology developments, and other key factors.

Should it be determined that a modeling framework is warranted that exceeds the current computational and conceptual limits on optimization modeling under uncertainty, it will be necessary to identify, among other things, appropriate decision criteria and the appropriate method for their application. In recent years, integrated assessment and energy systems models have been developed that can analyze much higher degrees of uncertainty than is possible in any of the several standard optimization-based frameworks (e.g., Lempert and Schlesinger 2000; Gritsevskyi and Nakicenovic 2000). These models allow for the assessment of a wide range of plausible scenarios of future events pertaining

[3] A similar point applies to the treatment of intergenerational equity and distributional issues. Because of the long timescales involved in climate policy analysis, assumptions regarding the rights and interests of future generations are unavoidable and have a substantial influence on the conclusions. The representation of these issues in the standard framework has been intensively critiqued (e.g., Howarth and Norgaard 1992; Howarth 2000).

to, for example, climate change, impacts upon natural systems, and developments in energy-related technology—in contrast to the conventional approach of specifying "most likely" or "baseline" scenarios and restricting analysis to essentially marginal deviations therefrom. In these approaches, Knightian or deep uncertainties (as well as conventional, or "probability-based" uncertainties) can be addressed directly through the use of a computation-intensive search through plausible realizations of future events. These models allow for a very broad range of possible future environmental and/or technological paths; however, a trade-off is that unique optimal equilibria or policy solutions cannot be determined. Instead, they use decision criteria such as "near-optimality": policy pathways that cannot be demonstrated to be globally optimal but satisfy partial optimality criteria in decision spaces of high dimension.

In summary, there is a critical need for research to develop different theoretical and computational possibilities for an integrated modeling capability that allows for both conventional and deep uncertainty, the analysis of robust strategies, and computationally intensive scenario analysis combining market and non-market elements. In an initial phase, this effort could be focused upon economic phenomena, quantities, and trends, with the aim of establishing a view of "possible futures" for the California economy as a basis for mitigation and adaptation analysis. One important element of this work would be to devise protocols for incorporating the existing modeling capabilities for specific sectors and systems that are currently in use by state analysts. In subsequent work, this overall effort can be enhanced and expanded to include the representation of natural systems in the state that may be threatened by climate change, and the appropriate policy pathways for addressing the risks from abrupt and/or extreme climate change.

3.2 Climate Change Impact Mitigation and Adaptation

The past decade has seen the emergence of an extensive body of research on the potential physical and socioeconomic impacts of climate change, summarized most recently in the authoritative assessment of the Intergovernmental Panel on Climate Change (IPCC 2001). A comprehensive assessment of potential climate change impacts on California under the auspices of the U.S. Global Climate Change Research Program, emphasizing water and ecosystem effects, is nearing completion (Wilkinson 2002).

The literature on the detailed, sector-specific economic consequences of climate change, while expanding, is more circumscribed. Integrated assessment, as discussed in the previous section, has tended to focus on aggregate national or international damages from climate change and aggregate costs of GHG abatement. Sector-specific economic analysis of climate impacts in the United States has been pioneered in work described in Mendelsohn, Nordhaus, and Shaw (1994, 1996), Mendelsohn and Neumann (1999), and Mendelsohn (2001). The methods developed in this work are being applied to a current analysis of the economics of climate change impacts in California, focusing on a number of specific sectors and systems, including agriculture, water, ecosystems, and timber. Among other findings, preliminary results both highlight vulnerabilities and indicate potentials for adaptation (e.g., changing the crop mix in state agriculture) and mitigating investments (e.g., to deal with coastal inundation).

These California-focused analyses suggest a wide range of both further refinements and additional research topics. The following discussion does not attempt a complete review, but instead addresses key specific research needs that are research priorities. The general aim here is to direct the analysis of California impacts research toward a focus on key risks and uncertainties, and toward developing models that provide policy makers with practical guidance for addressing them.

The economic research just described adopted scenarios of gradual climate change, localized to the California region. A next step, following the discussion in Section 3.1, is to incorporate scenarios of rapid and/or abrupt climate change, and to analyze the implications of potential extreme events. Proceeding in this direction requires in part further work in regional climatic modeling that is beyond the purview of this roadmap. However, there are several key elements to the economic component of such an effort. The first is the way in which researchers model the decision making of, and information available to, agents in the economy. An important development in recent research on the economics of climate impacts has been the incorporation of adaptive behavior on the part of economic agents (compare with the Mendelsohn et al. citations, preceding). In contrast to earlier approaches, recent work accounts for the adjustments that, for example, farmers will make to crop selection and growing practices when faced with climate change. This work assumes that economics agents exactly anticipate changes in climate that are relevant to production decisions—or in other words, have "perfect foresight" with regard to climate change.

These assumptions are less plausible, however, in the case of abrupt or strongly nonlinear climate change. Rapidly occurring climate change may overwhelm the ability of decision makers—notably in the agricultural sector—to adapt quickly enough to avoid losses. Similarly, complex nonlinear shifts in the climate regime may prove impossible to anticipate, forcing economic agents to adjust to change after the fact, and again reducing the possibility of minimizing losses. In the event that climate also shifts well outside historical experience, the magnitude of required changes in production techniques may itself be a source of super-normal economic costs. (As the National Research Council (2002) points out, the previous generation of economic research on climate impacts—eschewing adaptive and anticipatory behavior—may in fact be a more appropriate approach to modeling abrupt climate change.)

The discussion in Section 3.1 applies here also: Incorporating nonlinear or abrupt climate change into economic models will require extension and reformulation of current sectoral impact models. Minimally, it requires models to have an intrinsic stochastic structure, in order to represent the very substantial uncertainties involved. In addition to further modeling research, there is a need for further empirical work to better understand the potential magnitudes of losses in the event of abrupt and/or extreme climate change. This work could include, for example, surveying existing records on weather-related disaster damages. A central aim should be to identify particular climate-related "thresholds" in specific systems, the crossing of which would result in discontinuous increases in damages.

A second research topic is how to explicitly incorporate the current institutional constraints on existing systems into economic models. These constraints are typically not represented in standard optimization models. They will be of considerable importance, however, in formulating policy responses to climate change. This issue is particularly important in modeling California's complex water infrastructure and how it may be affected by climate change.

A third research need is to analyze impacts on additional, economically significant sectors of the California economy, and to further study potential non-market damages from climate change. (EPRI 2002 includes an analysis of one category of potential biodiversity loss from climate change in California.) Priority sectors include recreation and tourism, both of which are important in the state economy and both of which may be vulnerable to climate impacts. The valuation of non-market damages, as noted above in Section 3.1, is a difficult problem. Conventional integrated assessments of the costs of climate change and the benefits of mitigation characteristically omit these damages, which reflect the potential effects of climate change on "services" that are provided by natural systems outside of market institutions. Examples include biodiversity and the various amenities that individuals derive from non-impacted ecosystems. It is widely recognized that this systematic omission has resulted in underestimation of the benefits of climate change mitigation. From an economic standpoint, the key feature of such impacts (and the reason for their omission) is that there are no observable price data that can be used to incorporate them into the cost-benefit calculus. Techniques for their economic evaluation have been developed in recent decades; these techniques fall under the general rubric of "contingent valuation" (CV), which is a set of methods for eliciting preferences for goods or services for which markets (and therefore prices) do not exist. An authoritative review conducted in 1993 by the National Oceanic and Atmospheric Administration concluded that, "CV studies can produce estimates reliable enough to be the starting point for a judicial or administrative determination of natural resource damages" (Arrow et al. 1993), but CV methods remain controversial. (One limitation of this method for climate change analyses is that the damages may be suffered by future generations whose preferences are impossible to elucidate now.) An appropriate research focus would be to assess the applicability of CV for evaluating specific potential non-market damages in California, combined with an assessment of other possible valuation methods. In addition, any effort in this area should be fully coordinated with biological and physical scientists, to ensure that full account is taken of the state-of-the-art in scientific understanding of the natural phenomenon or system in question (Roughgarden 1995).

3.3 The Determinants of Energy Demand and Energy-related Technological Change

California's energy system will be a focus of climate-related policy making in several ways. First, climate change will change patterns of energy use, resulting in potential shifts in supply requirements. Second, climate change will affect the nexus between the energy and water systems, with further supply implications. The third aspect, which is the focus of this section, is that the energy system will be a major focus of carbon mitigation policies.[4] Thus, estimating the costs of carbon abatement from a number of policies directed at altering energy demand patterns—including tradable carbon emissions permits, vehicle emissions limits, and end-use energy-efficiency standards—will be a central problem for California's policy makers.

The potential magnitude of these costs is possibly the single most controversial topic in energy and climate policy in the United States. The current U.S. national policy position on climate change is essentially based on the conclusion that achieving large-scale increases in energy efficiency or significant levels of carbon mitigation would entail unacceptably large economic costs. At the same time, however, both the national and many state and local governments—including California's—maintain long-standing policies and programs to promote energy efficiency under the assumption that the direct (i.e., non-environmental) benefits of these measures exceed their costs.

This contradiction is but one indicator of a much more fundamental, and long-standing, debate in energy economics and analysis, focused on the performance of markets in allocating privately and socially optimal levels of energy efficiency. A central focus of research should be to substantially improve estimates of the costs of reducing energy demand, increasing energy efficiency, and otherwise reducing carbon emissions by means of intervention in the energy system. This section focuses on three core research topics that are addressed to this goal.

3.3.1 Economics of the Energy-Efficiency "Gap"

The 1970s saw the emergence of a long-running debate between economists and energy technologists on the degree to which energy-efficient technology is optimally allocated by markets in the absence of policy intervention. The focus of this debate has been the so-called "energy efficiency gap": the putative under-adoption of such technology without government policies to encourage (or compel) it. (This is also commonly referred to as the "top-down/bottom-up" debate.) Technologists have consistently argued that the gap is both real and substantial, while economists have strongly questioned this claim on both theoretical and empirical grounds. Long a theme in energy policy, the debate over the "gap" has, with little or no amendment, been absorbed into climate policy as well.

[4] It will not be the exclusive focus of such policies, because biological carbon sequestration may also play a significant role in California.

Both technology-based and economics-based work on this issue proceeds apace. In the policy arena, however, at least at the highest levels of decision making, the views of economists have strongly prevailed: For all intents and purposes, official U.S. national policy on climate change categorically rejects the possibility of large-scale, low-or-zero cost carbon abatement through technology-focused interventions.[5] Nonetheless, the existence and magnitude of an energy-efficiency gap remains very much an open question. It is clearly a central concern for research and policy measures on mitigation. Whether or not there is indeed widespread, systematic under-investment (relative to economic criteria) in energy efficiency by consumers and firms has major implications for estimating the economic costs of intrastate carbon abatement via either the "top-down" (e.g., carbon emissions permits) or the "bottom-up" (e.g., energy-performance standards) paths.

The most striking feature of this debate is how little intellectual progress has been made toward resolving it.[6] There have been some efforts by economists to find common conceptual ground (e.g., DeCanio 1993, 1998; Howarth and Sanstad 1995; Howarth and Andersson 1993). In general, however, the analytical methods and arguments commonly brought to bear by both "camps" of antagonists differ almost not at all from those of two decades ago. Technologists continue to posit "market barriers" to energy efficiency without providing rigorous theoretical and empirical elaborations of this idea, while economists continue to apply theoretical models that rule out a priori the possibility of an energy-efficiency gap, despite a host of apparent empirical evidence to the contrary.

This debate is commonly framed as one over the merits of energy-efficient *technology.* At a fundamental level, however, it is in fact an argument over the nature of energy-related *decision making.* Fortunately, as in the field of large-scale simulation modeling, there have been advances in the economics of decision making that hold considerable promise for progress in resolving the energy-efficiency gap debate. These advances have appeared in what is called "behavioral economics," a discipline that links economics with psychology and other behavioral sciences in the study of decision making (Mullainathan and Thaler 2000). Behavioral economics has been stimulated in large part by a growing body of empirical evidence that the standard economic model of rational behavior—"expected utility maximization"—has critical empirical shortcomings as a description of individual decision making.

[5] A recent effort to integrate "top-down" and "bottom-up" findings at the national level is described in Krause et al. (2002); this work also discusses the exclusive reliance by the U. S. government on 'top-down' analysis in assessing the Kyoto Protocol.

[6] In the early to mid-1990s, there was some initial movement toward constructive engagement—at least on the terms of debate, stimulated in part by the widely cited paper by Sutherland (1991). These issues were a focal point of the Stanford University Energy Modeling Forum (EMF) study (EMF 13) on "Markets for Energy Efficiency" (REF). The October 1994 special issue of the journal *Energy Policy,* which arose from the EMF meetings, presented a variety of viewpoints on the "gap," from both economists and technologists (Huntington et al. 1994). Unfortunately, this potential opening for more productive interactions among the parties to the "top-down/bottom-up" debate has for the most part remained unexploited.

Behavioral economics provides a natural setting for a renewed and, hopefully, more productive effort to understand the nature of energy-related decision making and the character and magnitude of the energy-efficiency gap. The first step in a program of research should be a careful assessment of the empirical literature on the efficiency "gap." The goal would be to scrutinize the putative evidence of anomalies in consumers' and firms' energy-efficiency choices to determine the robustness of these anomalies when account is taken of quality and character of data, uncertainty and hedonic elements, and related factors.[7]

The second step should be to apply new models of intertemporal decision making that take account of, and seek to explain, empirical evidence against the standard discounted utility model (e.g., Loewenstein and Prelec 1992). Two phenomena are of particular interest here: "loss aversion," or the asymmetric weighting of gains and losses with respect to a neutral reference point, and "hyperbolic discounting," a widely observed pattern that stands in contrast to the conventional exponential discounting model. These and other concepts and their theoretical and empirical elaborations hold considerable promise for breaking the impasse over the energy-efficiency "gap."

3.3.2 Microeconomics of Technological Change and Energy Productivity

In the conventional representation of the economy that is embodied in most IA models, there are two mechanisms through which the economy can reduce its use of energy, whether in absolute or relative terms. First is substitution: in response to a change in relative prices, consumers and firms will tend to shift away from relatively higher to relatively lower-priced goods and services. In the case of energy, a carbon or energy tax, or a system of tradable emissions permits that raised the price of energy, will result in substitution away from energy in general, or specific carbon-intensive fuels in particular. In accord with standard behavioral and equilibrium assumptions, such substitution is costly by definition.

The other mechanism is technological improvement that, over time, reduces the relative energy-input requirements of producing goods and services. With few exceptions, such improvement is represented in the models as "autonomous" or "exogenous": it occurs over time independent of price changes or policies. More specifically, by assumption, it *cannot be affected by prices or policies.* It is well known that assumed rates of autonomous energy-saving technological change can have major effects on model estimates of the costs of carbon-abatement policies, because of the effects of these rates on baseline trajectories. Thus, for example, if the economy is becoming 1% more efficient each year "on its own," then policies to reduce energy use of carbon emissions in the future need be less stringent than if this rate is, say, 0.5%.

[7] The evidence for the "gap" has been frequently criticized for being "engineering" in character and failing to take account of economic fundamentals. However, much of this evidence was in fact the product of research by econometricians applying discrete choice methods, and is rather consistent across a range of studies.

This representation of technological change, however, while conventional and all but universal in IA modeling, would seem to omit a potentially significant additional mechanism for reducing energy use or carbon emissions. For example, suppose that a carbon tax or emissions permit system were introduced. One would speculate that the resulting new incentives for energy efficiency or carbon efficiency would also result directly in new technological improvements. That is, engineers, scientists, and entrepreneurs would recognize the newly profitable opportunities for inventing and marketing energy- or carbon-saving technology, and the resulting technical progress would serve to increase energy or carbon efficiency in addition to the substitution and autonomous effects described above.

This effect is commonly described as "induced" or "endogenous" technological change (ETC).[8] This phenomenon has been a central focus of research on economic growth since the mid-1980s, following the seminal work of Romer (1986, 1990). A closely related topic is the phenomenon of "learning-by-doing" (LBD) in production of new energy supply technologies, that is, production cost declines as experience is gained in manufacturing. The LBD phenomenon has been extensively studied and documented in a variety of cases (not restricted to energy technology) over decades of empirical study, and has recently been an active research topic in energy economics.

The significance of ETC and LBD in climate policy has been a topic of debate in recent years, particularly with respect to whether its omission in standard models creates a bias toward overestimating the costs of carbon abatement. A number of studies have shown that including either ETC or LBD in computable general equilibrium models (described in Section 3.1, preceding) can lower the costs of meeting emissions abatement targets, relative to simulations in which they are omitted (Goulder and Schneider 1999; Manne and Richels 2002; Popp 2002). Recent partial equilibrium (that is, single-market) work on the empirical measurement of ETC has also indicated that it may be a significant factor in determining the rate of energy-saving technological progress in specific technological categories (Newell et al. 1999; Popp 2000).

Understanding how ETC and LBD affect the evolution of California industries—and the potential costs and benefits of intrastate mitigation policies—should be a high research priority. Initially, emphasis should be placed upon econometric analysis of historical trends in state industries. Further work would seek to apply the results in a CGE or other integrated modeling framework.

This work should at least in part take advantage of firm-level longitudinal economic databases (primarily for manufacturing) that have become available in the past decade. (The best known of these is the U.S. Census Bureau's "Longitudinal Research Database" (LRD); see McGuckin and Pascoe (1988) for an early description.) The advent of these empirical resources has stimulated a new generation of microeconomic research and has

[8] It is important to note that this discussion pertains to technological invention by the private sector, as opposed to R&D undertaken directly by the government.

resulted in a rather dramatic expansion of the understanding of the behavior of firms, markets, and technological change—particularly in manufacturing (Bartelsman and Doms 2000). An important research frontier is to extend this work to encompass energy trends, with a particular emphasis on ETC and LBD.

3.3.3 Information Technology and Energy Trends

Despite the current cyclical downturn, an expert consensus has emerged that the development and diffusion of information technology (IT) is largely responsible for the upward shifts in aggregate labor and total factor productivity in the U. S. economy since the mid-1990s (Jorgenson and Stiroh 2000; Oliner and Sichel 2000). This conclusion has been mitigated, but not reversed, with the recent downward revisions by the U. S. Bureau of Economic Analysis of late-1990s productivity acceleration: productivity growth still remains well-above the "doldrums" of the two decades following the first oil shocks of the 1970s.

Simultaneous with this shift, there has been an acceleration in the decline of the U.S. aggregate Energy-to-GDP (E/GDP) ratio, the most aggregate index of overall energy intensity in the economy.[9] This has raised conflicting speculation regarding the direct or indirect contributions of IT to energy productivity. It has been claimed, for example, both that IT is directly improving energy efficiency on a broad scale (Romm 2000), and that the change is instead due to temporary shifts in weather patterns (Hakes 2000). A preliminary statistical study indicates that approximately one-half the acceleration in E/GDP post-1996 could be accounted for by milder-than-usual weather, indicating a possible, but not demonstrated, effect of IT on aggregate energy demand patterns (Davis et al. 2002).

Analyzing the aggregate and micro, direct and indirect, implications of the IT "revolution" for energy demand in California is an extremely important topic in the context of climate policy: large-scale impacts of IT could have a significant effect on both baseline energy trends and the costs of GHG abatement policies. At the aggregate (state economy) level, a more careful decomposition study of recent trends should be undertaken, accounting for price changes, weather patterns, structural or sectoral shifts in the composition of state economic output, and related factors. At the micro level, detailed examination of the costs and benefits to individual consumers and firms of the new generation of electronic energy-management tools should be carried out. The key challenge for the latter work will be obtaining the appropriate data. Work to date on firm-level productivity impacts of IT has relied upon specially constructed data sets in which firm output, labor use, conventional capital investments, and prices are combined with information on hardware and software investments (e.g., Brynjolfsson and Hitt 2000). This line of research, however, has not yet been extended to incorporate energy use—carrying out this extension should be a high research priority.

[9] The same pattern is observed in the California energy-to-gross state product ratio (author's calculations).

3.4 Integrated GHG Mitigation Policies and Crosscutting Issues

3.4.1 Revenue Recycling

In analyzing strategies for climate change mitigation, economists have focused primarily on the possible use of price instruments—such as carbon taxes and tradable emissions permit systems—that would reduce energy demand and/or cause a shift away from carbon-intensive fuels. Were they to be implemented, such measures could result in considerable revenue accruing to the government. This is a given in the case of carbon or other emissions taxes, and would occur in the case of tradable permit systems if the permits were auctioned or otherwise sold, rather than allocated at no cost (or "grandfathered") to emitters.

The term *revenue recycling* refers to the return of such monies back into the economy. (Early results are reported in Shackleton et al. 1992; a general review of research and findings on this topic through the mid-1990s is given in Goulder 1996.) The standard economic model of public finance is built on the premise that taxes on specific goods or services are "distortionary" in the sense that they cause consumers and firms to change their behavior—specifically, to substitute away from the taxed item. This "distortion" may in fact result in an improvement in economic efficiency, for example, in the case of taxing an environmental pollutant. In the case of taxes on labor or investment used to finance government operations, while there may also a social benefit (in the form of a government program), the taxes themselves entail some economic loss resulting from the reduction in incentives to work or invest.

The central idea of revenue recycling is to use carbon revenues *to offset other distortionary taxes*. More exactly, carbon revenues would be used to hold the government's budget constant while reducing *marginal* tax rates on labor or investment. This strategy would reduce the "distortions" caused by these taxes, and thus result in economic efficiency gains beyond the benefits of reducing carbon emissions. Put differently, carbon policy would be linked with fiscal policy.

Revenue recycling in the context of carbon abatement has been an active topic of research over the last decade. It is now well-established in the economics literature that the judicious use of carbon revenues would lower—perhaps substantially—the economic costs of carbon abatement relative to other approaches.[10,11] This topic is therefore of considerable interest in analyzing potential mitigation efforts in California. Analyzing the possibilities for carbon abatement with attendant revenue recycling within California is an

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[10] *Other approaches* here refers in particular to "grandfathering" of permits, in which case there are no revenues to recycle, and to so-called "lump-sum" rebating of revenues, which has no effect on existing tax distortions.

[11] One important, indeed central, focus in the revenue recycling literature has been the so-called "strong double dividend hypothesis": whether use of emissions revenues to offset preexisting distortionary taxes would, per se, yield net economic gains *even without the accompanying environmental benefits.* In other words, would revenue recycling "pay for itself" as a fiscal, as opposed to environmental, policy? Following early optimism on this point, the expert opinion converged on a rejection of the strong double dividend hypothesis (e.g., Bovenberg and DeMooij 1994). Recent work, however, is lending new credence to the hypothesis (Parry and Bento 2000).

appropriate topic for conventional dynamic general equilibrium modeling. The key problems to be solved in such an analysis include translating existing techniques and theory for "closed" economies into an "open" economy setting. This terminology refers, in essence, to the distinction between an economy that is assumed to have active trade links with the outside (e.g., California) as opposed to being self-contained (e.g., the United States, to a first approximation for this purpose). In addition, the structure of taxation in the California economy differs critically in at least one key respect from that of the U.S. economy: state income taxes, which would be one possible "target" for revenue recycling, are fully deductible from federal taxes, so that marginal reductions in these taxes would not have the efficiency-enhancing effects found in the more general case. This difference would require a more nuanced approach to modeling the disposition of carbon revenue.

3.4.2 Multi-gas Strategies, Ancillary Benefits of CO_2 Emissions Reductions, and Regional Air Quality

Traditionally, climate policy analysis has focused on CO_2 abatement. However, several IA modeling groups have recently called attention to the importance of integrating CO_2 with other gases in devising mitigation strategies, primarily methane (CH_4) and nitrous oxide (N_2O), but also perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) (Reilly et al. 1999; Manne and Richels 2000). Their findings include substantial cost reductions resulting from a multi-gas (as opposed to a CO_2-only) approach to implementing the Kyoto Protocol, with little difference in climate or ecosystem effects between the two.

At the same time, it is known that a number of policies to control CO_2 emissions would also have the effect of reducing emissions of other pollutants, with important implications for regional air quality. Examples include reductions of particulate matter, SO_X, NO_X, lead, and volatile organic compounds (VOCs). Moreover, these reductions would yield health and other benefits on a much shorter timescale than that applying to climate-change-mitigating effects of CO_2 reductions. As a consequence, the costs of CO_2 mitigation actions are likely to be reduced once analyses account for these "co-benefits" or "ancillary benefits." For example, recent analyses of electric power sector emission indicate that a $10/ton tax on carbon emissions would yield approximately $3 of health benefits from NO_X reduction (Burtraw et al. 1996). Similarly, a recent multi-sector, integrated analysis of energy demand in the European Union found that CO_2 abatement policies would reduce the costs of controlling acidification and ground-level ozone sufficiently to compensate up to 20% of the energy system costs related CO_2 control (Syri et al. 2001).

Such results demonstrate the importance of integrating carbon and non-carbon mitigation measures both analytically and in the formulation of California policy. Given the State's strong commitment to maintaining air quality, as well as the likelihood of broad climate-related mitigation efforts in the coming decades, there will be a clear need for a multi-gas approach that fully exploits potential synergies and reaps ancillary benefits. In the case of electric power, the analytical methods for estimating such ancillary benefits are well established and have been applied to national U.S. studies. A California-focused analysis of this sector should be carried out using existing models localized to the California economy. The key tools in such an analysis would be an electric sector model, applied to the Western Systems Coordinating Council (WSCC) NERC region, and a model of pollutant transport. A broader, multi-sector analysis of the links among CO_2 abatement and that of other gases in a policy and economic framework is also a priority. Such an effort will require the development of new analytical tools for application to California.

3.4.3 Developing Regional Markets for GHG Trading

Emissions trading has emerged in recent years as a favored instrument for reducing GHG emissions, specifically as an alternative to direct government regulation of emissions through "command and control" measures. An emissions trading system imposes a "cap" on the total emissions of a given set of pollutants that are allowable from a sector or from an entire economy, and distributes permits to emitters that place a cap on their individual emissions. Emitters can trade these permits among themselves, however, and will do so when the costs of abatement vary among emitters. The result is that a given unit of abatement will be undertaken by whichever emitter can do so at the lowest cost, thereby minimizing the aggregate cost of meeting the overall emissions cap.

Long favored by economists, this idea has gained considerable currency as a result of its successful implementation in 1990 to reduce SO_2 emissions from electric power generators. Emissions trading has been strongly favored by the United States in international negotiations, and is currently being studied as a means of reducing non-SO_2 emissions from U. S. power generation. There is a very high likelihood that some form of emissions trading system—national, international, or both—will eventually be put into place to achieve GHG mitigation targets.

In the meantime, however, smaller-scale trading regimes are being studied and in some cases implemented. The mechanisms under consideration include both the standard "cap and trade" approach and schemes for "offset" exchanges of varying geographical scope. This work provides a starting point for considering trading regimes that would operate within California. Such programs could be implemented as stand-alone state responses to climate change or could be mounted in response to national or international agreements.

3.4.4 Estimating Costs of Abatement of Non-CO_2 gases

As noted in Section 3.4, several well-known IA models now include abatement cost estimates for non-CO_2 greenhouse gases, and the simulation results are indicating substantial potential cost reductions in GHG mitigation from a multi-gas approach. The method used in these assessments is to develop supply, or marginal cost, curves for abatement from each such gas, relating levels and costs of reduction on an economy-wide basis.

These efforts provide the starting point for an important enhancement of the standard, CO_2-focused, approach, but require further development to ensure their accuracy and reliability. First, the theoretical foundation of the current approach assumes away the possibilities of abatement at negative net cost (Hyman 1997). That is, it is assumed that there are no inefficiencies or barriers that would allow GHG gas abatement measures whose direct benefits exceeded their costs. Although such inefficiencies or barriers may indeed be limited in practice, an improved theoretical treatment would allow for making the question one to be answered empirically. Second, current cost curves of this type do not directly account for the effects of technological improvement on lowering the costs of abatement—including the possibility of price-induced or "endogenous" technical change and the possibility of learning or experience effects that would also tend to lower costs (compare with Section 3.3). Finally, although the curves themselves are embedded in general equilibrium models, they are derived on a partial equilibrium basis, and therefore do not fully account for the linkages between abatement measures and the broader economy.

An appropriate topic for PIER is to develop and apply an enhanced methodology for the construction and measurement of these abatement cost curves. The research priorities would be to: (1) develop a theoretical model that allows for the possibility of negative cost measures and embeds cost-reducing technological change, and (2) apply this model to selected gases in the context of abatement within California.

3.5 The PIER Focus

The State needs to evaluate current methods and tools and develop new ones for evaluating the many economic aspects of GHG mitigation and adaptation. Such efforts must focus specifically on the State's unique needs.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Studying the economics of climate change mitigation and adaptation is one such issue. PIEREA aims to address this topic through its own targeted research and to attract collaborators that will share data and work with PIEREA.

Other PIEREA roadmaps address other economic, ecological, and technical aspects of GHG mitigation. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

At present, research needs to focus on the following areas:

1. Computational Modeling and Decision Analysis
2. Impacts and Adaptation Analysis
3. Behavioral Economics and Energy-Efficiency Investment
4. Characteristics of Energy-related Technological Change
5. Information Technology (IT) and Energy Trends
6. Revenue Recycling

7. Integrating Air Quality and Multi-gas GHG Abatement Strategies
8. Regional GHG Trading Markets
9. GHG Abatement Cost Modeling for Non-CO_2 GHGs

This section continues the discussion in Section 3, further discussing the status of current work and scientific and research gaps in these areas.

4.1 Computational Modeling and Decision Analysis

Several institutions have conducted intensive research on uncertainty, complexity, and related features in the context of climate change and energy policy over the past decade, as well as the on construction and application of models embodying these ideas and requiring computation-intensive solution techniques. Key among these are Rand, Carnegie-Mellon University, and the International Institute for Applied Systems Analysis (IIASA). The focus of this work is generally at a global scale, and no models exist that represent California per se.

Research Needs

For initial computable general equilibrium (CGE) analysis, researchers can use the E-DRAM general equilibrium model for California, developed at the University of California at Berkeley (Berck 2000). E-DRAM is an enhanced version of the DRAM model, which was developed for the California Department of Finance to conduct revenue and taxation analysis (compare with Section 4.6). The overall need is to design, construct, and apply an *integrated economic decision framework* and set of modeling tools for research and policy making related to climate change mitigation and adaptation in California. The goal of this effort would be to facilitate the formation of robust strategies within and across sectors. It would be designed to fully account for fundamental uncertainties and would leverage the State's substantial investment to date in detailed sector-specific modeling—notably for water resource and air quality management planning. Specific research elements would include: (a) reviewing and augmenting, as needed, the existing empirical resources for integrated modeling of the California economy, including state energy balances, input-output data, and estimates of technological change trends; and (b) designing an aggregate decision-analysis framework to determine robust climate mitigation and adaptation strategies at an aggregate level.

4.2 Impacts and Adaptation Analysis

The most relevant existing work was reviewed in Section 3. In addition to this work, researchers at the University of California at Berkeley have conducted a national-level study of the impacts of climate change on irrigated agriculture, and the methods used would be appropriate for application to the California agricultural/hydrological sector. Although a large number of non-market valuation studies have been carried out for a range of environmental "goods and services," there appear to be few or none focusing on climate change-related issues per se. A comprehensive list of such studies is available at the "Environmental Valuation Reference Inventory (EVRI)" Web site constructed and maintained by Environment Canada.[12]

Research Needs

The primary research needs are to: (a) extend current theory to incorporate impacts and adaptation behavior under uncertainty and in the context of rapid and/or severe climate change; (b) develop modeling tools for specific sectors that incorporate current institutional constraints; (c) review existing methods for non-market evaluation, assess their applicability to California, and (d) apply or extend them to study amenity impacts of climate change on California, to obtain initial estimates of non-market damages.

4.3 Behavioral Economics and Energy-Efficiency Investment

There appears to be no existing systematic effort to apply behavioral economics to the problem of energy-related decision making. However, behavioral economics in general (in other applications) is a very active research area at a number of American universities, including the University of California at Berkeley, the University of Chicago, and Carnegie-Mellon University. There is multi-departmental interest in developing a significant research effort on behavioral economics at the University of California at Berkeley (Hanemann 2001). (Note that one of the world's leading researchers in this area, Matthew Rabin, is on the faculty of the Economics Department at Berkeley.) Also of particular interest to PIER is the program on Behavioral Economics at the Russell Sage Foundation, which provides funding in this area.

Research Needs

The need is for a comprehensive program of research applying behavioral economics to energy demand studies, with a focus on consumer and firm decisions regarding energy efficiency. This effort would adapt and extend the state-of-the-art behavioral economic research on intertemporal decisions. It would be aimed at fundamental advances in understanding the nature of the so-called "energy-efficiency gap" and its implications for policies designed to accelerate the diffusion of energy-efficient technology.

[12] Although this is a subscription service, an overview of the EVRI can be accessed at: http://www.evri.ec.gc.ca/evri/english/tour.htm.

4.4 Characteristics of Energy-related Technological Change

Work on ETC and LBD is being conducted by a number American researchers, including economists at Resources for the Future (RFF), Stanford University, Syracuse University, and the Electric Power Research Institute. Broadly, as noted in Section 3, work in this area is divided between the construction of prototype general equilibrium models embodying ETC, and econometric studies of LBD and technological change in specific sectors. Active research efforts are under way to incorporate learning or experience curves into energy system models at the Energy Technology and Systems Analysis Programme (ETSAP) in the Netherlands and at the U. S. Department of Energy. Such work in the context of uncertainty modeling is an active focus at the International Institute for Applied Systems Analysis (IIASA) in Austria. Overall, these various projects provide a range of technical benchmarks to initiate a California-specific research effort.

Research Needs

The primary research needs are: (a) an econometric study of historical California data to identify the impacts on energy demand of endogenous technological change, learning effects, and policies; (b) construction of a state energy system model to apply the results of (a) in forecasting and the analysis of new and potential energy-efficient and/or low-GHG technologies. As noted in Section 3, this research should make use of available micro-level data. The scope and scale of the model in (b) would depend upon resources and programmatic considerations; a possible strategy is to adapt an existing model (or reduced form thereof) such as the MESSAGE model built at IIASA.

4.5 Information Technology (IT) and Energy Trends

This area is receiving much less attention from the analytical community than might be expected. (In the past several years, a disproportionate emphasis has been placed on the putative skyrocketing electricity consumption of the Internet; this claim has been conclusively repudiated (Koomey 2000)). The initial study referred to in Section 3 was undertaken by Lawrence Berkeley National Laboratory (LBNL). There has also been some work at Argonne National Laboratory, but this work is now approximately two years old. Currently, at the micro level, work is under way (sponsored by the California Energy Commission) on installing and evaluating energy management software tools and related measures as a peak-load demand management mechanism, but this does not entail thus far a careful economic analysis of the costs and benefits of this type of measure to firms.

Research Needs

The overall need is to understand how the rapid diffusion of IT is influencing energy demand in the California economy and the implications of this diffusion for the State's long-term energy trajectory. This work should examine, using econometric methods, the relations among the composition of gross state product (GSP), aggregate energy productivity trends, and the diffusion of IT as measured both by investment and by IT-related contributions to GSP. In addition, data permitting, it should examine at the micro level the effects of IT tools for energy management.

4.6 Revenue Recycling

A summary of the main themes in economic research on revenue recycling was presented in Section 3. For PIER, the most important fact is that a dynamic general equilibrium model of the California economy was constructed in the mid-1990s by researchers at the University of California at Berkeley for use by the state's Department of Finance (DOF) (Berck et al. 1996). This model, the Dynamic Revenue Analysis Model (DRAM), remains in use at the DOF. This model was designed explicitly for intrastate fiscal policy analysis.

Research Needs

The most direct path to studying revenue recycling in the California economy would be to apply the DRAM model, adding additional details on energy supply and demand and introducing carbon and/or energy taxes and/or revenues from tradable emissions permits. Such a project could draw on the extensive, but less technically sophisticated, work on state-level revenue recycling that has been carried out by the Center for a Sustainable Economy in Washington, D.C.

4.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A reasonably large body of work has been amassed under the rubric of "ancillary benefits" of climate change; much, although not all, of this work pertains to measures that simultaneously affect air quality and GHG emissions. A useful overview, with numerous applications (as well as international geographical coverage), was provided at a conference sponsored by the Organization for Economic Cooperation and Development (OECD) in March 2000.[13] A conceptual framework for analyzing ancillary costs and benefits is provided in Krupnick et al. (2000).

The joint organization State and Territorial Air Pollution Program Administrators/ Association of Local Air Pollution Control Officials has created a comprehensive framework for joint air quality and GHG mitigation policy planning (STAPPA/ALAPCO 1999). This work includes case studies of "harmonized options" in specific locations in the United States, including Ventura County, California.

In California, joint strategies are likely to focus more on the transportation sector than on the electric power sector (which has received the most attention in analyses to date). Nevertheless, California electricity generation may remain of interest in this context as attention is turned to regional or national emissions-trading mechanisms; in addition, potential fundamental shifts in this sector attributable to an accelerated deployment of renewables and distributed generation—as well as a movement toward combined-cycle generation—would have both air quality and GHG emissions implications. In the study of ancillary benefits from power generation measures, the state-of-the-art for the United States is represented by the work at Resources for the Future, a nonprofit research

[13] "Workshop on Assessing the Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies," OECD Environment, Washington, D.C., 27–29 March 2000.

organization in Washington, D.C. This work employs the so-called "HAIKU" electric power model and the "Transport and Analysis" (TAF) framework for analyzing atmospheric transport and environmental effects. There is active work under way on regional air quality modeling in California at LBNL and elsewhere, but this has not yet been linked to or integrated with GHG mitigation analyses. A recent and possibly unique multi-sector integrated analysis, using both an energy system model and an environmental impact model, is reported in Syri et al. (2001) and was carried out by a multi-institution team in Europe.

Research Needs

The fundamental research need is to develop of a statewide menu of "harmonized" measures on a multi-sector basis, estimate their costs and benefits, and create a protocol for their implementation. This effort will involve both empirical study and the adaptation of existing air quality modeling tools. It will also be necessary to coordination this research with the State's transportation planning infrastructure.

4.8 Regional GHG Trading Markets

A number of projects are under way to establish regional or otherwise localized trading regimes or protocols for "offset" projects on various geographical scales. Of particular interest for PIER is the "Chicago Climate Exchange," a regional trading scheme for the America Midwest, currently in the design phase with financial support from the Joyce Foundation.

Research Needs

The first need is a feasibility study for an intrastate trading market. Such a study would examine the appropriate geographical and sectoral scope, which GHGs would be included, required institutional mechanisms, and related elements. Subsequent research would focus on implementation issues in the context of emerging (or by-then established) national and international policies.

4.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

The current state-of-the-art in economic modeling of non-CO_2 abatement costs was discussed in the Background section, emphasizing that: (a) the current theoretical model for non-CO_2 gas abatement rules out by assumption the possibility of "negative-cost" abatement, and (b) does not account fully for technological change.

Research Needs

The research need is to further develop the existing standard model for non-CO_2 gas abatement to include the possibility of negative-cost measures and to explicitly represent cost-reducing technological change.

5. Goals

The goal of the Economics of Mitigation and Adaptation portion of the PIER Climate Change Research Plan is to help California formulate and assess the economic implications of implementing various mitigation and adaptation strategies.

The achievement of that goal depends on the development of innovative tools and approaches that enable researchers to better account for the economic aspects of mitigation and adaptation strategies.

The PIEREA program recognizes that much work is currently under way in these areas and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIEREA will identify existing efforts and form partnerships to leverage resources.

5.1 Short-term Objectives[14]

5.1.1 Computational Modeling and Decision Analysis

A. Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.

Activities needed: (1) Construct new energy balances for California, and apply them to an existing CGE model (E-DRAM) to analyze selected benchmark scenarios of climate impacts and mitigation policies. (2) Develop an integrated modeling framework for studying the California economy that allows for exploratory modeling under uncertainty of key aggregate quantities, including population, economic growth, energy use, and carbon emissions—as well as their responses to possible abatement policies and climate-related impacts. (3) Apply this model to determine an initial aggregate suite of robust strategies. (4) Develop a protocol and software tools for integrated analysis, linking this model with existing models of California systems and sectors. (4) Begin work to integrate within this framework models of key intrastate natural systems and their evolution in the coming decades.

Critical Factors for Success:

- Successful development, testing, and application of new models and software; effective application to California policy making.

5.1.2 Impacts and Adaptation Studies

A. Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change. Identify critical "thresholds" of

[14] S*hort-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

natural and economic systems under such change. Develop models to incorporate existing institutional constraints on key systems. Begin assessment of non-market values of intrastate climate change impacts.

Activities needed: (1) Conduct theoretical research to extend existing economic framework for sectoral impact cost estimation. (2) Conduct economic modeling of institutional elements in key systems. (3) Conduct empirical research, possibly including contingent valuation study, to value non-market impacts of climate change.

Critical Factors for Success:

- New benchmark estimates of climate change impact and mitigation costs in California.
- Successful application to policy planning in water, agriculture, and hydropower planning.
- Credible initial estimates of non-market damages in specific sectors.

5.1.3 Behavioral Economics and Energy Efficiency Investment

A. Establish a solid theoretical and empirical body of research on energy-related decision making, using a behavioral economics approach.

Activities needed: (1) Conduct a rigorous assessment of the empirical and theoretical literature on the energy-efficiency "gap." (2) Write a survey paper relating the "energy-efficiency gap" debate to recent advances in behavioral economics. (3) Conduct a technical research effort to construct and econometrically estimate or calibrate one or more specific models of energy-efficiency investment incorporating relevant concepts and techniques from behavioral economics.

Critical Factors for Success:

- Substantial advances in understanding the nature of energy-efficiency-related decision making by consumers and firms.
- Development and application to policy of new economic models of this type of economic decision.

5.1.4 Characteristics of Energy-related Technological Change

A. Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.

Activities needed: (1) Conduct an econometric study estimating the role of energy-related endogenous technological change and learning effects in California industries over the past three decades. (2) Based on those study results, develop forecasts of new technology costs and penetrations, and identify promising new technologies. (3) Develop or adapt a computational energy technology model to carry out economic and technological scenario studies (incorporating uncertainty) of the future evolution of the California energy system.

Critical Factors for Success:

- Empirical estimates of role and significance of ETC and LBD in California industries; application to integrated modeling and policy studies.

5.1.5 Information Technology and Energy Trends

A. Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.

Activities needed: (1) Apply the type of analysis sketched in the text—econometric studies of historical trends—to California (with appropriate technical enhancements of methods). (2) Conduct micro-level studies of the costs and benefits of IT energy-management tools to individual consumers and firms.

Critical Factors for Success:

- Understanding of the significance of IT in the California economy and its implications for future policies to abate GHGs in the state.

5.1.6 Revenue Recycling

A. Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.

Activities needed: (1) Enhance the DRAM (or E-DRAM) model described above as needed, to conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy. (2) Conduct a general equilibrium study at the scale of the statewide economy.

Critical Factors for Success:

- Estimates of the implications of appropriately designed revenue recycling policies for lowering the costs of GHG abatement in California.

5.1.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A. Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies, and incorporate these estimates into state-economy-wide integrated assessments of mitigation.

Activities needed: (1) Assess the GHG implications of current California air quality planning. (2) Develop an empirical basis for multi-gas strategies in climate change-related planning. (3) Formulate "harmonized strategies" for linked AQ and GHG abatement.

Critical Factors for Success:
- Successful design of integrated policies for achieving simultaneous air quality and GHG abatement goals in California.

5.1.8 Regional GHG Trading Markets

A. Assess the feasibility of intrastate markets for GHG trading and related mechanisms.

Activities needed: (1) Conduct a feasibility study of a California GHG "cap and trade" system, as well as of offset programs for various gases, and an initial design study for such systems.

Critical Factors for Success:
- An applicable assessment of the potential for intrastate trading markets, and completion of a preliminary design for one or more such markets.

5.1.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

A. Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.

Activities needed: (1) Theoretical research to extend current economic models to incorporate possible negative-cost abatement and to improve representation of cost reductions attributable to technological change.

Critical Factors for Success:
- Development of improved methods for modeling and measuring costs and benefits of non-CO_2 gases.

Table 1. Short-term Budget

Objective	**Projected Cost ($000 per year)**
5.1.1.A Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.	500
5.1.2.A Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change. Identify critical "thresholds" of natural and economic systems under such change. Develop models to incorporate existing institutional constraints on key systems. Begin assessment of non-market values of intrastate climate change impacts.	300
5.1.3.A Establish a solid theoretical and empirical body of research on energy-related decision making, using a behavioral economics approach.	300
5.1.4.A Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.	300
5.1.5.A Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.	150
5.1.6.A Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.	100
5.1.7.A Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies, and incorporate these estimates into state-economy-wide integrated assessments of mitigation.	200
5.1.8.A Assess the feasibility of intrastate markets for GHG trading and related mechanisms.	150
5.1.9.A Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.	150
Total Short-term Cost per Year	**2,100**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected per-year expenditure over the short-term period.

5.2 Mid-term Objectives

5.2.1 Computational Modeling and Decision Analysis

A. **Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.**

Activities needed: (1) Continue the model and software development indicated in the short-term. (2) Link and expand the strands developed in the short-term to include more sectors, systems, and details.

5.2.2 Impacts and Adaptation Studies

A. **Extend sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change, and to incorporate institutional constraints. Continue assessment of non-market values of intrastate climate change impacts.**

Activities needed: (1) Continue, as needed, the short-term research. (2) Apply research results to empirical studies.

5.2.3 Behavioral Economics and Energy Efficiency Investment

A. **Establish a solid theoretical and empirical body of research on energy-related decision making using a behavioral economics approach.**

Activities needed: (1) Continue the short-term theoretical and empirical research. (2) Expand the short-term work to incorporate these models in a computational equilibrium setting.

5.2.4 Characteristics of Energy-related Technological Change

A. **Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.**

Activities needed: (1) Continue the short-term theoretical and empirical research. (2) Incorporate the short-term results into computational modeling of the costs and benefits of GHG abatement within California.

5.2.5 Information Technology and Energy Trends

A. **Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.**

Activities needed: (1) Extend the line of research developed in the short-term to determine the potential role of such technologies for designing and implementing large-scale GHG abatement.

5.2.6 Revenue Recycling

A. **Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.**

Activities needed: (1) Expand the short-term work to a more geographic-and-sector detailed analysis. Study both the micro-level details and impacts of potential revenue recycling schemes, as well as the possibility of micro-level applications of the revenue recycling ideal.

5.2.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A. **Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies and incorporate these estimates into state-economy-wide integrated assessments of mitigation.**

Activities needed: (1) Continue as needed the research indicated in the short-term objectives. (2) Incorporate the short-term results into policy planning.

5.2.8 Regional GHG Trading Markets

A. Assess feasibility of intrastate markets for GHG trading and related mechanisms

Activities needed: Continuation of short-term work as needed, and begin implementation as appropriate.

5.2.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

A. Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.

Activities needed: Apply short-term results to empirical studies.

5.3 Long-term Objectives

5.3.1 Computational Modeling and Decision Analysis

A. **Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.**

Activities needed: (1) Create, apply, and develop a multi-institution effort that includes universities, state agencies, and non-governmental organizations that will focus on computationally intensive decision-modeling of climate change mitigation and adaptation.

5.3.2 Impacts and Adaptation Studies

A. **Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change, and to incorporate institutional constraints. Continue assessment of non-market values of intrastate climate change impacts**

Activities needed: (1) Incorporate research results into policy planning.

5.3.3 Behavioral Economics and Energy Efficiency Investment

A. **Establish a solid theoretical and empirical body of research on energy-related decision making using a behavioral economics approach.**

Activities needed: (1) Fully include behavioral economic principles in computational energy-economic and integrated assessment models.

5.3.4 Characteristics of Energy-related Technological Change

A. **Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.**

Activities needed: (1) Incorporate the short- and mid-term results into simulation modeling of the costs and benefits of GHG abatement within California.

5.3.5 Information Technology and Energy Trends

A. **Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.**

Activities needed: (1) Continue to extend the short- and mid-term research to determine the potential role of such technologies for designing and implementing large-scale GHG abatement.

5.3.6 Revenue Recycling

A. **Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.**

Activities needed: (1) Continue to expand this work to a more geographic-and-sector detailed analysis. That is, continue to study both the micro-level details and impacts of potential revenue recycling schemes, and the possibility of micro-level applications of the revenue recycling ideal.

5.3.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A. **Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies and incorporate these estimates into state-economy-wide integrated assessments of mitigation.**

Activities needed: (1) Incorporate research results into policy planning.

5.3.8 Regional GHG Trading Markets

A. Assess feasibility of intrastate markets for GHG trading and related mechanisms.

Activities needed: (1) Implementation of research as appropriate.

5.3.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

A. Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.

Activities needed: (1) Application of research results to policy planning.

6. Leveraging R&D Investments

6.1 Methods of Leveraging

Much of the work identified in this roadmap would be collaborative with other entities; PIEREA would either co-fund projects by other entities or use outside funds to support PIEREA efforts.

The research direction proposed in the roadmap represents something of a departure from well-established channels. With respect to drawing significant federal support, PIER funding of the suggested research should be considered "seed money." That is, successful execution, with PIER support, of the research topics proposed here is very likely to lead to new or intensified interest and support from other agencies.

Research on the economics and integrated assessment of climate change has been and continues to be funded by a variety of federal agencies, as well as by industry. Among the key public funding sources are the "Method and Models for Integrated Assessment" special program of the National Science Foundation (NSF), the core NSF Economics and Decision Sciences programs, and the "Integrated Assessment" program Office of Biological and Environmental Research in the Department of Energy. In addition, the U.S. Environmental Protection Agency provides support for certain research in this area. The other research areas discussed above are of a fundamental nature, and as such, receive support from the National Science Foundation in particular.

6.2 Opportunities

Co-sponsorship opportunities are likely with the National Science Foundation, the Office of Biological and Environmental Research in the Department of Energy, and with other programs under the auspices of the U.S. Global Change Research Program. No specific collaborative opportunities have been identified.

7. Areas Not Addressed by This Roadmap

This roadmap does not contain a recommended research area that is specific to the transportation sector. It should be noted, however, that several of the areas recommended for research bear directly or indirectly on transportation. More generally, transportation issues will have a prominent place in climate change mitigation and adaptation in California. It is assumed that implementation of work recommended in this roadmap will be articulated with ongoing research and policy work on transportation by the Energy Commission, other state agencies, academic institutions, and non-governmental organizations.

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Appendix A
Current Status of Programs

This section outlines those efforts that most closely address the economics of climate change mitigation and adaptation in California. It should be noted that research relating to the topics presented in this roadmap is under way at literally hundreds of sites around the world. This section provides a selected list focusing on academic departments, research centers, and other organizations rather than upon individual researchers. (Many of the latter are listed in the References and their work discussed in the text of the roadmap.)

Current Status: California

Environmental Defense, Washington, D.C.
Completed study of climate change impacts on Los Angeles and Southland.

Lawrence Berkeley National Laboratory
Ongoing work on technologies and measures for demand response and load management.

National Center for Ecological Analysis and Synthesis, University of California at Santa Barbara
Completed report on climate change impacts on California.

Rand, Santa Monica, California
Ongoing work on California energy, water, and environmental issues.

Current Status: Regional, National, and International

Department of Agricultural and Resource Economics, University of California at Berkeley
Ongoing basic and applied economic research on climate change, forestry, water resources, and agriculture.

Energy Technology Systems Analysis Programme (ETSAP), Petten, The Netherlands
Ongoing work on learning effects in energy technology diffusion and energy system modeling.[15]

EPRI, Palo Alto, California
Ongoing work on energy—including electricity sector technology and evolution—and on climate change impacts.

[15] ETSAP is a permanent program of the OECD International Energy Agency (IEA).

International Institute for Applied Systems Analysis, Vienna, Austria
Ongoing work on energy systems and technology and modeling under uncertainty.

Lawrence Berkeley National Laboratory
Ongoing work on energy aspects of information technology.

Office of Renewable Energy and Energy Efficiency, U. S. Department of Energy, Washington, D.C.
Ongoing work on learning curves in energy technology.

Rand, Santa Monica, California
Ongoing work on robust strategies for climate policy, agent-based modeling, and computer-assisted decision making.

Resources for the Future, Washington, D.C.
Ongoing work on climate economics, ancillary benefits of GHG mitigation, and technological change.

State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials, Washington, D.C.
Completed report, as well as ongoing work, on "harmonized options" for air quality and GHG mitigation.

U.S. Global Climate Change Research Program (USGCRP)
Interagency coordinating program for research on all aspects of global climate change. Sponsoring entity for the U.S. National Assessment of the Potential Consequences of Climate Variability and Change.